Direct UV/Optical Imaging of Stellar Surfaces: The Stellar Imager (SI) Vision Mission

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ABSTRACT

The Stellar Imager (SI) is a UV/optical, space-based interferometer designed to enable 0.1 milli-arcsecond (mas) spectral imaging of stellar surfaces and, via asteroseismology, stellar interiors and of the Universe in general. SI's science focuses on the role of magnetism in the Universe, particularly on magnetic activity on the surfaces of stars like the Sun. SI's prime goal is to enable long-term forecasting of solar activity and the space weather that it drives, in support of the Living with a Star program in the Exploration Era. SI will also revolutionize our understanding of the formation of planetary systems, of the habitability and climatology of distant planets, and of many magneto-hydrodynamically controlled processes in the Universe. SI is a "Flagship and Landmark Discovery Mission" in the 2005 Sun Solar System Connection (SSSC) Roadmap and a candidate for a "Pathways to Life Observatory" in the Exploration of the Universe Division (EUD) Roadmap (May, 2005). We discuss herein the science goals of the SI Mission, a mission architecture that could meet those goals, and the technologies needed to enable this mission. Additional information on SI can be found at: http://hires.gsfc.nasa.gov/si/.

Keywords: stars, stellar surfaces, magnetic activity, dynamos, interferometry, high resolution imaging, exo-planets, habitability

1. INTRODUCTION

Magnetic fields affect the evolution of structure throughout the Universe and, in particular, drive the stellar activity which is key to life's origin and survival. However, our understanding of how magnetic fields form and evolve is currently very limited. Our close-up observations of the Sun has enabled the creation of approximate dynamo models, but none of these models predict reliably the future level of magnetic activity of the Sun or any other star. Major progress requires us to move beyond a concentration solely on the Sun and to search out an understanding of stellar magnetism in general. This general understanding is only possible through a "population study" in which we obtain maps of the evolving patterns of magnetic activity and subsurface flows and observe the internal structure and rotation of stars with a broad range of masses, radii, and activity levels. This improved understanding will, in turn, provide a major stepping stone toward deciphering magnetic fields and their roles in more exotic, complex, and distant objects, including active galactic nuclei, supernovae and planetary nebulae, interacting binary systems, and cool, evolved giant and supergiant stars. At the revolutionary design resolution of SI, sequences of images will also show us the dynamics of astrophysical processes and perhaps even allow us to directly see, for the first time, the evolution of, e.g., a planetary nebula, an early supernova phase, mass exchange in binaries, (proto-)stellar jets, and/or accretion systems in action.

The SI observatory concept, its science goals, and technology requirements were the subject of a "Vision Mission" Study commissioned by NASA HQ and executed in 2004-2005. The study was lead by the Goddard Space Flight Center, in collaboration with a broad variety of industrial, academic, and astronomical institute partners, as well as an international group of science and technical advisors. The results of that study were summarized in a previous SPIE article by Carpenter et al. (Ref. 1) and the full report is available on the SI website at http://hires.gsfc.nasa.gov/si/. In the current paper we provide an update on the mission concept and related technology development efforts.

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2. SCIENCE GOALS AND REQUIRED CAPABILITIES

2.1 Science Goals

The primary science goals of SI are to understand:

- **Solar and Stellar Magnetic Activity and their impact on Space Weather, Planetary Climates, and Life**
- ***Magnetic Processes* in general and their roles in the *Origin & Evolution of Structure* and in the *Transport of Matter* throughout the Universe**

With regard to the first goal SI is designed to address a number of specific questions, including:

- what do the internal structure and dynamics of magnetically active stars look like?
- what sets the dynamo strength and pattern in each star?
- how can active stars form polar spots?
- what can we expect next from the Sun, on time scales from hours to centuries?
- what causes solar-type 'Maunder minima' or 'grand maxima'?
- why do 2 in 3 Sun-like stars show *no* cycles?
- how does magnetic activity drives all aspects of "space weather" and affect planetary climates and life?

These questions will be addressed by spatially resolving stellar disks to map evolving atmospheric activity as a tracer of dynamo patterns and by asteroseismic probing (to at least degrees of order 60) of internal stellar structure and flows in a stars of various masses, radii, and activity levels.

The second goal is very broad in concept, but is enabled by the high angular resolution and spectral energy information provided by SI for the fine structure of a wide variety of heretofore unresolved objects and processes, including, for example:

- **Stellar interiors** *in solar and non-solar type stars*
- **Infant Stars-disk systems** *to image dynamic accretion, magnetic field structure & star/disk interaction*
- **Exo-planets** – SI will be able to image transits across stellar disks and perhaps in some cases directly image the planets themselves, if Fizeau nulling techniques can be developed to sufficient levels
- **Hot Stars** *and their hot polar winds, non-radial pulsations, rotation, structure, and the envelopes and shells of Be-stars*
- **Cool, Evolved Giant & Supergiant Stars** *and the spatiotemporal structure of extended atmospheres, pulsation, winds, shocks*
- **Supernovae & Planetary Nebulae:** *their core structure, early expansion and interaction with CSM*
- **Interacting Binaries,** *including mass-exchange, dynamical evolution, accretion, and dynamos*
- **Active Galactic Nuclei**, *including the transition zone between Broad and Narrow Line Emitting Regions and the determination of the origin and orientation of their jets*
- **Quasars, Black-Hole Environments**, etc.

Fig. 1 shows illustrations of the views that SI will enable of a variety of objects, including the surface and interior of a solar type star at 4pc, the magnetospheric-disk interaction region of a forming star, the surface of an evolved supergiant star at 2 kpc distance, and the resolution of AGN Broad Emission Line Regions (BELR) geometries and inclinations.

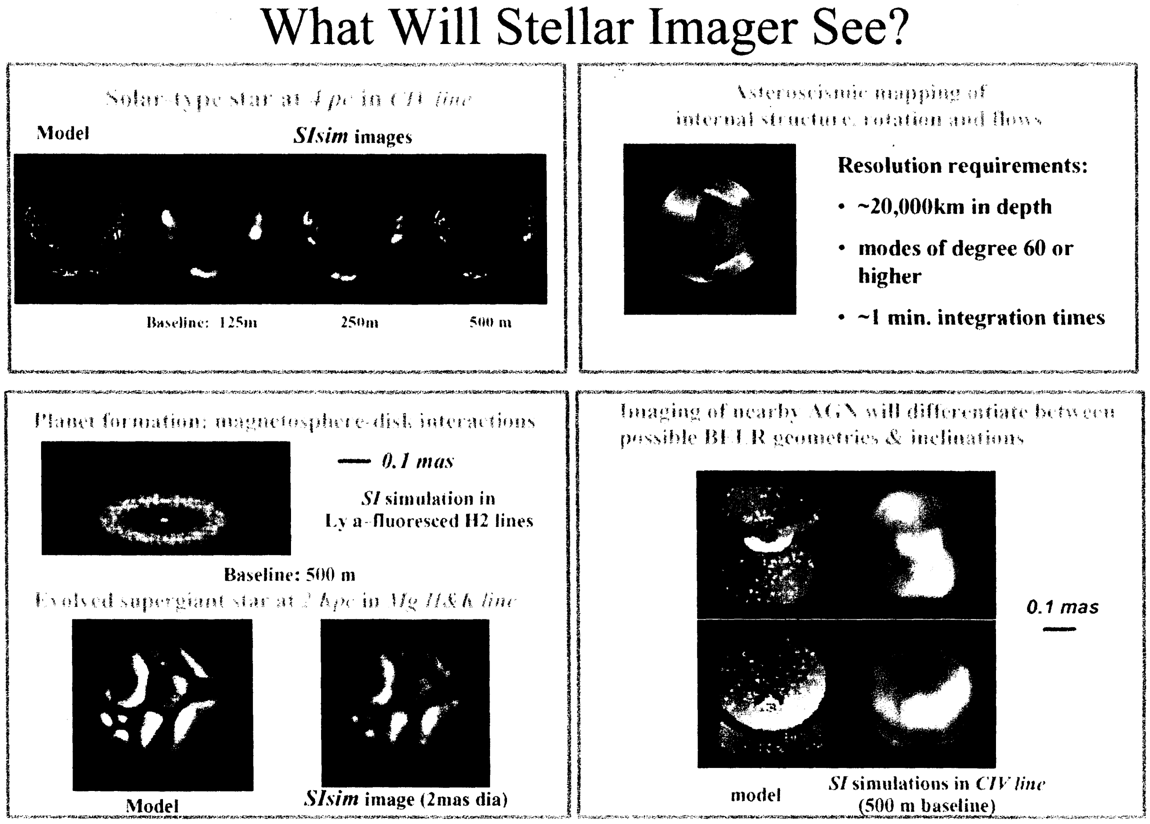


Fig. 1. Simulations of observations that will be possible with SI at various wavelengths and baselines, computed with SISIM (Rajagopal et al., Ref. 2). SI will resolve details never before seen on stellar surfaces and interiors, in both main sequence and evolved stars, probe protostellar disks, and enable the characterization of the BELR geometries and inclinations in AGN, amid many others objects and processes.

2.2 Importance of Stellar Imager to NASA/ESA Strategic Science Goals and to Society

SI addresses basic questions of great importance to Society and to the overall NASA and ESA Science Plans. Paramount in importance is the understanding, and the enabling of reliable prediction, of the effect of the Sun and its variations on the climate and habitability of Earth and other planets in our solar system, and in a broader sense, the effect of the central stars of exo-planetary systems on the climate and habitability of planets around these stars. We know from the history of our own planet that Solar variations are capable of significantly lowering or raising the mean global temperature of the earth – periods of "Grand Maxima" produce a "global warming" independent of the effects induced by humans (as in the 12^{th} and early 13^{th} centuries, while lower temperatures during the "Maunder Minimum" in the late 1600's induced crop failures in northern Europe (as well as allow people to skate on the River Thames in England during July!). These longer-term "climate" changes are accompanied by shorter-term changes due to solar flares, which can disable satellites and power grids, endanger astronauts in transit to the Moon or Mars, and even increase oil and gas pipeline corrosion by inducing strong electrical currents in the long, linear metal tubes. The "ensemble" population study proposed with SI will enable the understanding and prediction of these events and impacts on a much faster timescale than possible based solely on observations of a single star like the Sun over the many decades needed to observe it through multiple magnetic activity cycles and capture the full range of its variations and the resultant constraints on dynamo theory. SI will also open up a tremendous new "discovery space" in terms of angular resolution at ultraviolet and optical wavelengths, improving over that obtained with HST by a factor of more than 200x – an improvement that will, as always, lead to many unanticipated discoveries across a broad range of astronomical topics.

2.3 Capabilities Required to Meet Science Goals

In order to address these science goals, SI must have a wavelength coverage from just below hydrogen Lyman α to just above the Balmer Hα line, approximately 1200 – 6600 Å.

The UV region is important to enable access to emission lines from Lyα at 1216 Å to Mg II 2800 Å for stellar surface imaging and to provide important diagnostics of most abundant elements, as well as provide much higher contrast between magnetic structures and background than possible in the optical. Observing in the UV allows an architecture with significantly smaller baselines: the UV saves a factor of 2-4x vs. the optical due to the shorter wavelengths, and the active regions themselves are ~5x larger when viewed in the UV, thus leading to a savings of at least 10x in the required baselines. It must be possible to isolate the light of emission lines in ~10-Å UV pass bands, so that lines such as the C IV 1550 Å (100,000 K) and Mg II h&k 2800 Å (10,000 K) doublets can be cleanly seen against the general disk continuum.

High time resolution, spatially-resolved asteroseismology will require broadband, near-UV or optical light (3,000-10,000K) to provide sufficient signal to enable the resolution of internal structure and flows (modes to at least degrees of order 60 need to be detectable via resolved light variations across the disk, with approximately 100 resolution elements over the surface observed with a 1 minute cadence.)

The driving angular resolution requirement is ~50 micro-arcsec at 1200 Å (120 mas @2800 Å), to provide at least 1000 pixels of resolution over the surface of nearby (4pc) dwarf stars and thus enable the observation of typically-sized active regions over the full UV spectral range.

Energy resolution/spectroscopy of detected structures of at least R=100 is needed.

Mission lifetime must be relatively long, ~ 10 years, to enable the study of significant fractions of stellar activity cycles, which range from 8 – 23 years (versus the 11 year solar cycle) – this means that individual telescopes/hub(s) need to be designed to be refurbished or replaced in-situ.

3. MISSION ARCHITECTURE

As part of the Vision Mission Study, we have developed a "strawman architecture" or baseline mission design that satisfies all of the above requirements, as shown in Figures 2 and 3 below.

The current baseline architecture concept **(Fig. 2, top)** for the full Stellar Imager (SI) mission is a space-based, UV-Optical Fizeau Interferometer with 20-30 one-meter primary mirrors, mounted on formation-flying "mirrorsats" distributed over a parabolic virtual surface whose diameter can be varied from 100 m up to as much as 1000 m, depending on the angular size of the target to be observed. The individual mirrors are fabricated as ultra-smooth, UV-quality flats and are actuated to produce the extremely gentle curvature needed to focus light on the beam-combining hub that is located at the prime focus from 1 – 10 km distant. The focal length scales linearly with the diameter of the primary array: a 100 m diameter array corresponds to a focal length of 1 km and a 1000 m array with a focal length of 10 km. The typical configuration has a 500 m array diameter and 5 km focal length. A one-meter primary mirror size was chosen to ensure that the primary stellar activity targets can be well observed with good signal/noise. Sizes up to two meters may be considered in the future, depending on the breadth of science targets that SI is required to observe – e.g., some fainter extragalactic objects may need larger mirrors, but those will come at a cost to the packaging for launch, the number of launches needed, and total mission cost. The mirrorsats fly in formation with a beam-combining hub in a Lissajous orbit around the Sun-Earth L2 point. The satellites are controlled to mm-micron radial precision relative to the hub and the mirror surfaces to 5 nm radial precision, rather than using optical delay lines inside the hub for fine tuning the optical path lengths. A second hub is strongly recommended to provide critical-path redundancy and major observing efficiency enhancements. The observatory may also include a "reference craft" to perform metrology on the formation, depending on which metrology design option is chosen. **Fig. 2 (bottom)** shows two launch concepts that are quite feasible with current vehicles – depending on the number of hubs to be launched initially, either one or two launches will suffice to lift the entire observatory to Sun-Earth L2. **Fig. 3** provides an overview of the selected architecture: the upper panel shows a cross-sectional schematic of the entire observatory, while the lower panel shows a close-up of the hub and its major components.

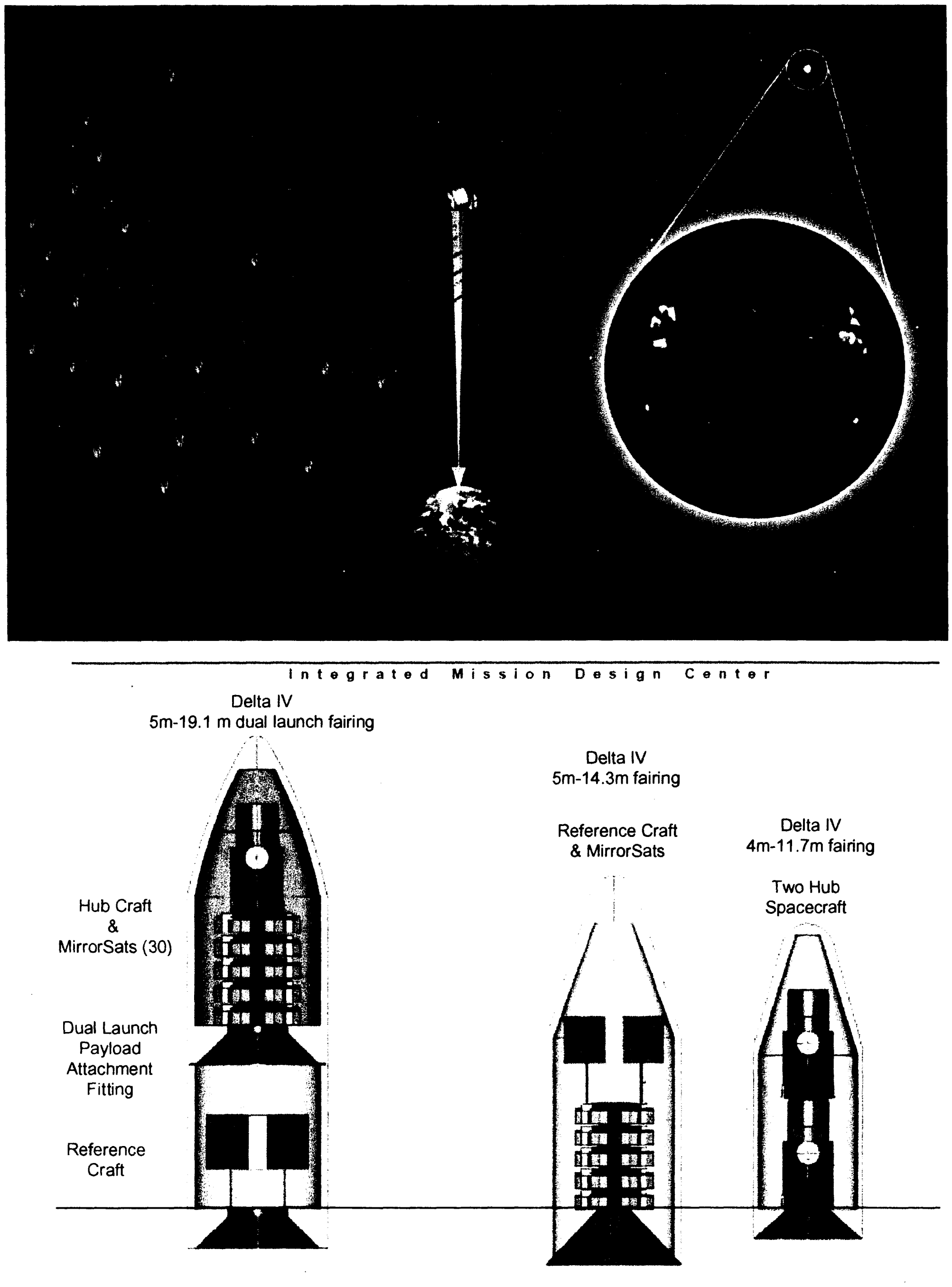
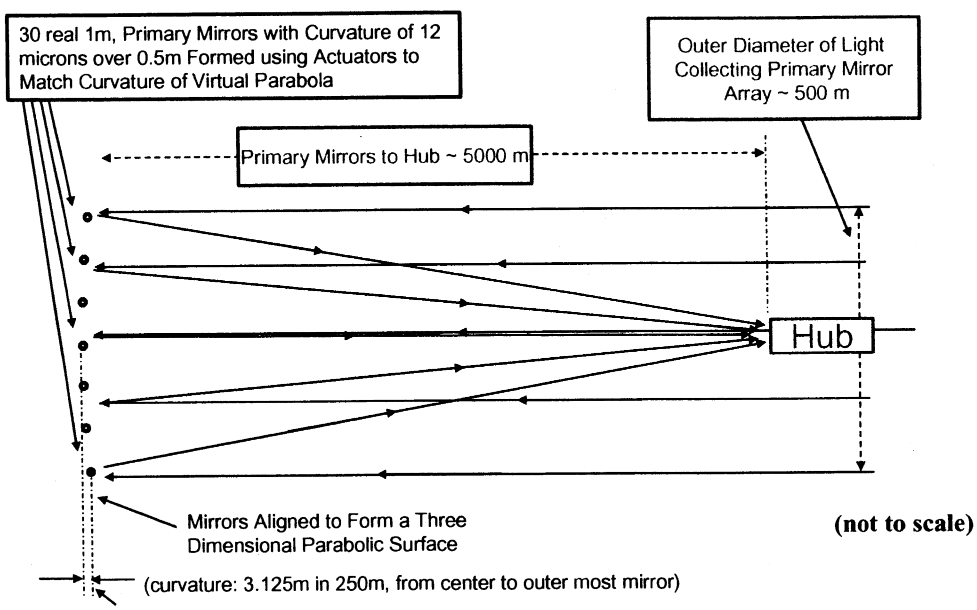


Fig. 2. Artist's concept of one possible architecture and two alternative launch concepts (depending on whether one or two hub spacecraft are to be launched initially) for SI. The upper panel shows a 0.5 km diameter, space-based UV-optical Fizeau Interferometer, located in a Lissajous orbit around the Sun-Earth L2 point, and comprised of 20-30 primary mirror elements (mounted on formation-flying "mirrorsats") that focus light on a beam-combing hub 5 km distant. The lower panel (left) shows that the entire observatory could be launched in a single Delta IV vehicle, if the large 5m-diameter, 19.1m high dual-launch fairing was used and only 1 hub were to be launched initially. If two hubs were included in the initially launch, then a dual-launch with smaller fairings on each would suffice (right).

SI Cross-Sectional Schematic



Principal Elements of SI Hub

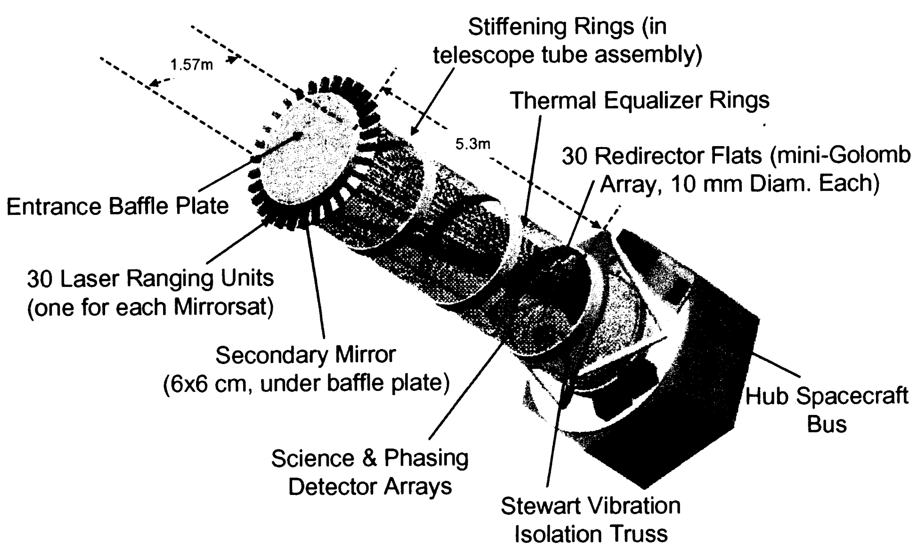


Fig. 3. A cross-sectional view (top) of the SI design and some details on the beam-combining hub (bottom).

4. TECHNOLOGY REQUIREMENTS AND DEVELOPMENT PLANS

The major technologies needed to enable the SI mission as described in this paper are summarized in **Table 1**. Probably the most difficult of these is the precision formation flying of as many as 33 distinct spacecraft: 30 mirrorsats, 1-2 beam-combining hubs, and possibly a reference spacecraft for metrology and aspect control. This is a complicated, multi-stage controls problem. However, similar control systems will be needed for many future missions - at some level, all missions composed of distributed spacecraft flying in a formation with tight constraints - so there is a great deal of motivation for such development.

Table 1: The major enabling technologies needed for Stellar Imager

- **formation-flying of ~30 spacecraft**
  - deployment and initial positioning of elements in large formations
  - real-time correction and control of formation elements
    - staged-control system (km → cm → nm)
  - aspect sensing and control to 10's of micro-arcsec
  - positioning mirror surfaces to 5 nm
  - variable, non-condensing, continuous micro-Newton thrusters
- **precision metrology over multi-km baselines**
  - 2nm if used alone for pathlength control (no wavefront sensing)
  - 0.5 microns if hand-off to wavefront sensing & control for nm-level positioning
  - multiple modes to cover wide dynamic range
- **wavefront sensing and real-time, autonomous analysis and control**
- **methodologies for ground-based validation of distributed systems**
- **additional challenges (perceived as easier than the above)**
  - mass-production of "mirrorsat" spacecraft: cost-effective, high-volume fabrication, integration, & test
  - long mission lifetime requirement
  - light-weight UV quality mirrors with km-long radii of curvature (using active deformation of flats)
  - larger format (6 K x 6 K) energy resolving detectors with finer energy resolution (R=100)

We have developed a notional roadmap for the development of Space Interferometry, which can be used as a guide as we proceed toward such missions. **Fig. 4** shows a logical progression from current ground-based testbeds and interferometers, through small space technology demonstrations and/or science missions, up to the large "Strategic" or "Vision" missions that will do true high resolution imaging.

Current technology development technology work for SI is concentrated on the development of cm-to-micron-level precision formation flying methodologies and algorithms and of techniques for sensing and controlling placement of individual mirrors in a many-element sparse array at the nm-level. Three testbeds (Ref. 3) being used for this development are shown in **Fig. 5**. The GSFC/MSFC/MIT Synthetic Imaging Formation Flying Testbed (SIFFT; K. Carpenter, R. Lyon, P. Stahl, D. Miller) is being used to develop cm-level formation flying algorithms on laboratory hardware, including formation deployment/maintenance, array reconfiguration, and synthetic imaging maneuvers. SIFFT uses the MIT-developed SPHERES on the MSFC Flat Floor facility to test theoretical control algorithms. It has successfully demonstrated formation control of 3 floating SPHERES and reconfiguration by both rotation and expansion/contraction of the array. The GSFC Formation Flying Testbed (FFTB; J. Leitner, E. Stoneking, J. Mitchell, R. Luquette) is a software simulation facility used to develop and demonstrate deployment of array spacecraft and a multi-stage acquisition of target light from individual mirrors by the beam-combiner. E. Stoneking has simulated all stages of formation/target light acquisition for the full-up SI. The Fizeau Interferometer Testbed at GSFC (FIT; K. Carpenter, R. Lyon, A. Liu, D. Mozurkewich, P. Petrone, P. Dogoda) is developing and demonstrating closed-loop, nm-level optical control of a many-element sparse array using wavefront sensing of the science data stream (no external metrology). It will be used in the future to develop and assess imaging synthesis algorithms and to develop nulling techniques for Fizeau Interferometers that might be used for planet detection and imaging. The ultimate goal of all these efforts is to develop staged-control methodologies covering over 12 orders of magnitude, from nm to km scales.

We are also studying alternative optical designs for SI to optimize its imaging and spectral energy resolution capabilities (Mozurkewich, Carpenter, and Lyon, Ref. 4).

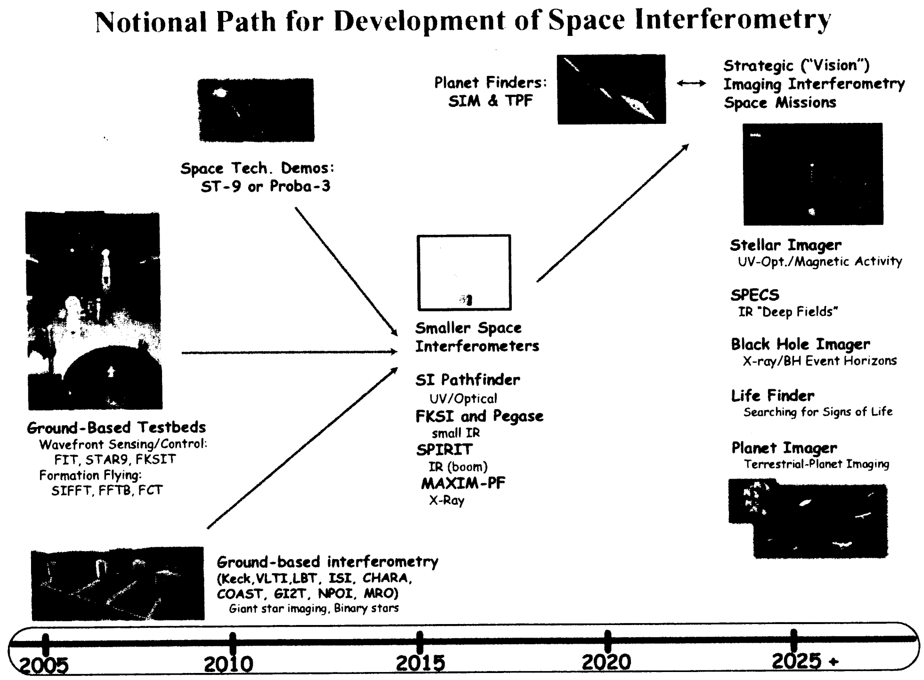


Fig. 4. A chart showing one possible development flow toward large-baseline interferometers in space, outlining a procession from the current ground-based facilities, to moderate-sized (20-50m baselines, 3-5 element arrays) space-based missions, up to the end goal of true high-resolution imagers operating across the electromagnetic spectrum.

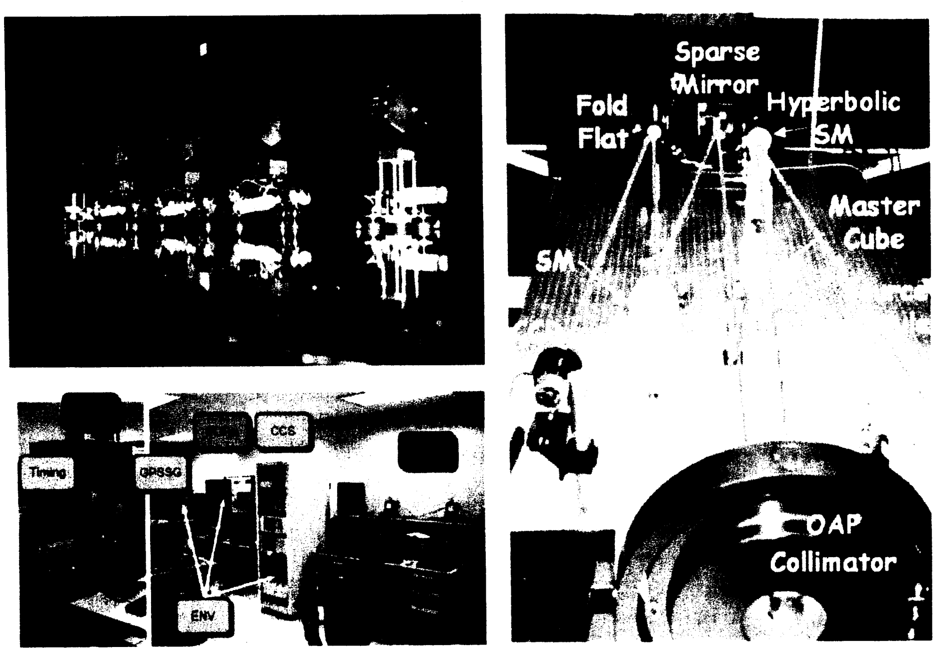


Fig. 5. Three ground-based testbeds developing technologies for Stellar Imager and other space-based interferometers: SIFFT (top left), FFTB (lower left), and the FIT (right). See text for details.

Next in sequence after the ground-based work are the smaller space-based interferometers. **Fig. 6** summarizes the characteristics of a "Stellar Imager Pathfinder" mission which the SI Team is developing as a possible "Origins Probe" level mission that could potentially fly in the latter part of the next decade and do both important new science as well as demonstrate technologies needed for future Strategic interferometry missions.

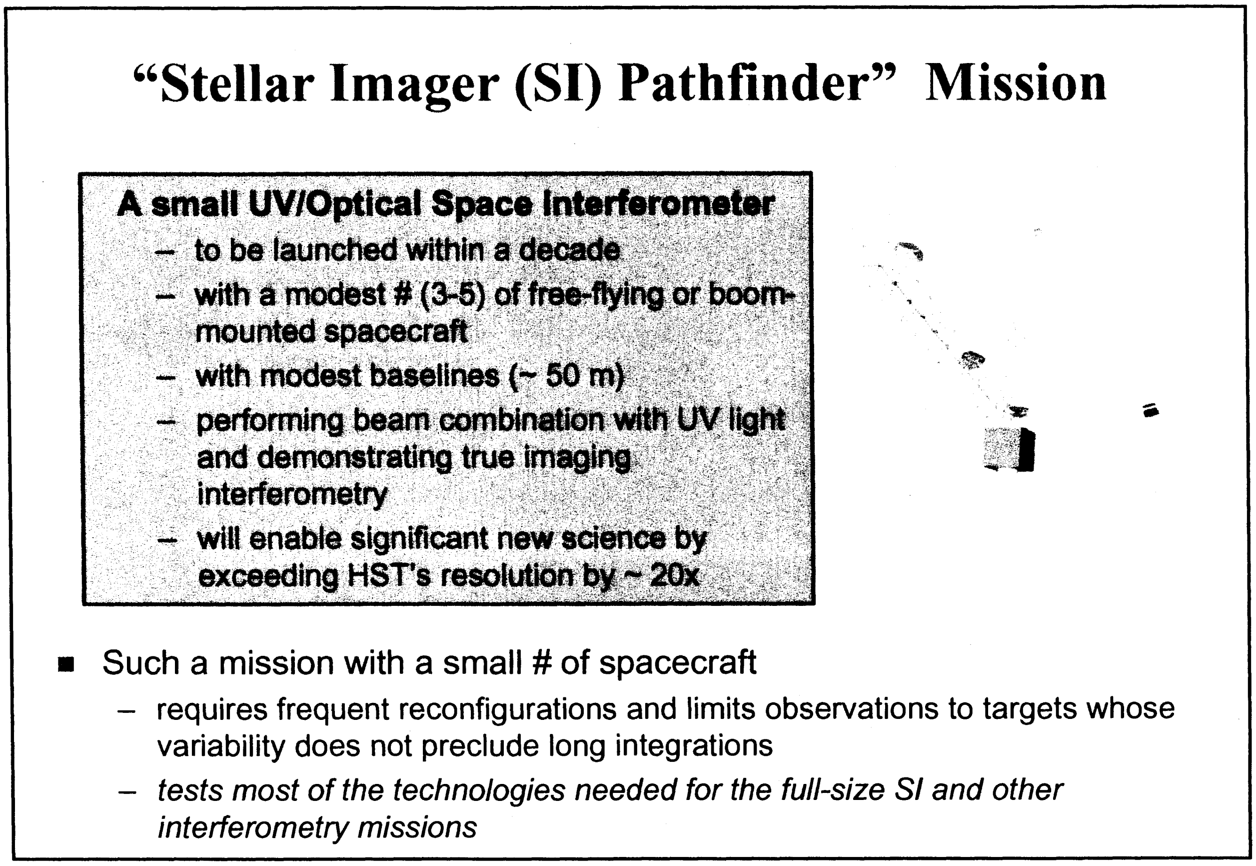


Fig. 6. A Stellar Imager Pathfinder mission would do major new science, as well as develop technologies need for SI and other future, larger interferometry missions.

5. STATUS OF THE STELLAR IMAGER

SI has been in the NASA SEC/SSSC/Heliospheric Division Roadmaps since the year 2000. It was selected in 2003 by NASA HQ for concept development as a NASA "Vision Mission". NASA/GSFC established partnerships and collaborations with a broad set of institutions and individuals to execute the Vision Study and continues to work with this broader Team to develop the science goals, architectural designs, and the needed technologies for SI. In 2005, SI was included in the Heliospheric Roadmap as a Flagship (Landmark Discovery) mission, as shown in **Fig. 7**. SI is also a candidate "Pathways to Life Observatory" in the 2005 EUD Roadmap. The SI Team is also working with the ESA "Luciola" Cosmic Vision Team to take advantage of synergies that might be accomplished due to the overlapping science goals and technology needs of the two missions.

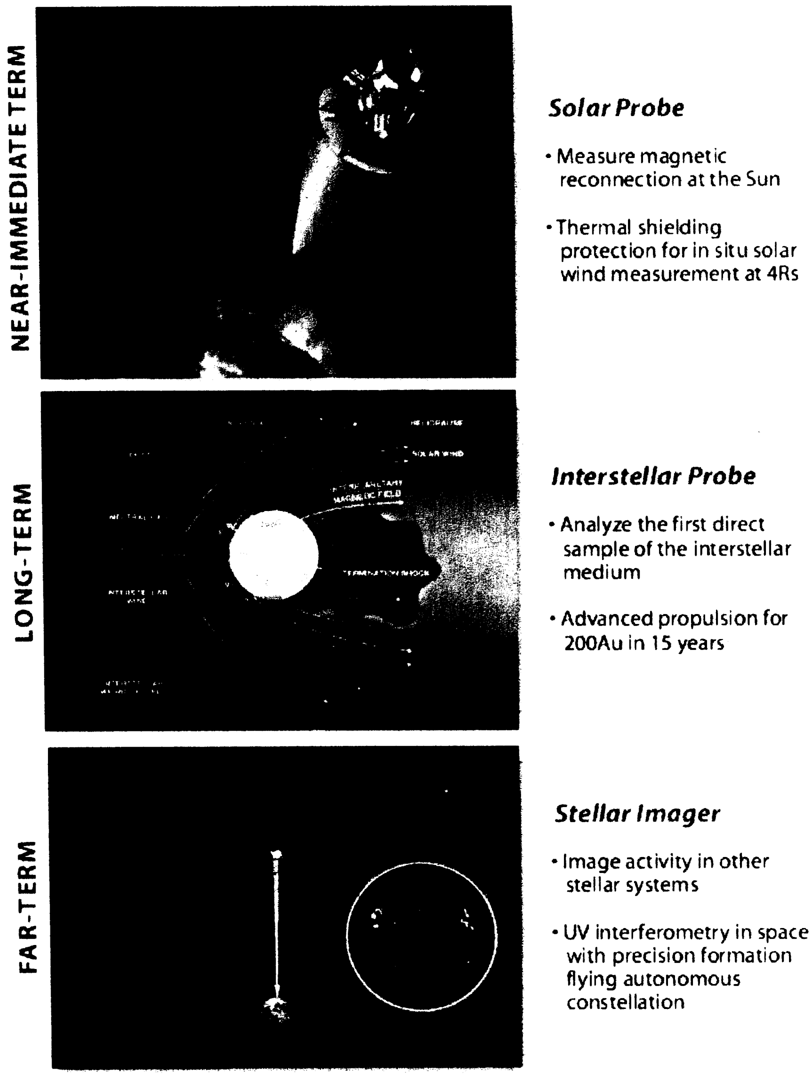


Fig. 7. "Landmark Discovery (aka, "Flagship") Missions" contained in the 2005 SSSC/Heliospheric Division Roadmap. Stellar Imager is the far-term component of that sequence.

6. SUMMARY AND CONCLUSIONS

The mission of the Stellar Imager is to enable an understanding of solar/stellar magnetic activity and its impact on the:

- origin and continued existence of life in the Universe
- structure and evolution of stars
- habitability of planets

and to study magnetic processes and their roles in the origin and evolution of structure and the transport of matter throughout the Universe. The SI Vision Mission Study has developed in detail the scientific goals and requirements of the mission, a baseline observatory architecture, the technology development needs of that and alternative architectures, a roadmap for that technology development, considered deployment and operations scenarios, and addressed operations assurance and safety issues. **Table 2** summarizes SI, its science goals, and its mission and performance parameters.

The study and subsequent technology work has shown that the scientific capabilities of such an ultra-high angular resolution UV/Optical interferometer are extraordinary, that credible design options are available, and that a sensible technology development path for supporting the development of the facility can be defined. SI fits well with the NASA and ESA strategic plans and complements other defined and conceptual missions, such as TPF, LF, and PI, and supports our collective desire as a species to understand extra-solar planetary systems and the habitability of surrounding planets, as well as improve our understanding of our own Sun and its impact on earth's climate and it's future habitability.

Additional information on the Stellar Imager can be found at http://hires.gsfc.nasa.gov/si/

Table 2: Summary of the Stellar Imager (SI) Vision Mission

Mission Overview		
SI is a UV-Optical, Space-Based Interferometer for 0.1 milli-arcsecond (mas) spectral imaging of stellar surfaces and stellar interiors (via asteroseismology) and of the Universe in general.		
Science Goals		
To understand: - Solar and Stellar Magnetic Activity and their impact on Space Weather, Planetary Climates, and Life - Magnetic Processes and their roles in the Origin and Evolution of Structure and in the Transport of Matter throughout the Universe		
Mission and Performance Parameters		
Parameter	**Value**	**Notes**
Maximum Baseline (B)	100 – 1000 m (500 m typical)	Outer array diameter
Effective Focal Length	1 – 10 km (5 km typical)	Scales linearly with B
Diameter of Mirrors	1 - 2 m (1 m currently)	Up to 30 mirrors total
λ-Coverage	UV: 1200 – 3200 Å Optical: 3200 – 5000 Å	Wavefront Sensing in optical only
Spectral Resolution	UV: 10 Å (emission lines) UV/Opt: 100 Å (continuum)	
Operational Orbit	Sun-Earth L2 Lissajous, 180 d	200,000x800,000 km
Operational Lifetime	5 yrs (req.) – 10 yrs (goal)	
Accessible Sky	Sun angle: $70° \leq \beta \leq 110°$	Entire sky in 180 d
Hub Dry Mass	1455 kg	Possibly 2 copies
Mirrorsat Dry Mass	65 kg (BATC) - 120 kg (IMDC)	For each of up to 30
Ref. Platform Mass	200 kg	
Total Propellant Mass	750 kg	For operational phase
Angular Resolution	50 μas – 208 μas (@1200–5000Å)	Scales linearly ~ λ/B
Typical total time to image stellar surface	< 5 hours for solar type < 1 day for supergiant	
Imaging time resolution	10 – 30 min (10 min typical)	Surface imaging
Seismology time res.	1 min cadence	Internal structure
# res. pixels on star	~1000 total over disk	Solar type at 4 pc
Minimum FOV	> 4 mas	
Minimum flux detectable at 1550 Å	5.0×10^{-14} ergs/cm^2/s integrated over C IV lines	10 Å bandpass
Precision Formation Fly.	s/c control to mm-cm level	
Optical Surfaces Control	Actuated mirrors to μm-nm level	
Phase Corrections	to λ/10 Optical Path Difference	
Aspect Control/Correct.	3 μas for up to 1000 sec	Line of sight mainten.

7. ACKNOWLEDGEMENTS

Contributions are gratefully acknowledged from the wide range of science and technology investigators and collaborators on the Stellar Imager Vision Mission Team (see **Table 3**). This work was supported, in part, by Vision Mission Study grants from NASA HQ to NASA-GSFC and from GSFC to Smithsonian Astrophysical Observatory, Seabrook Engineering, SUNY/Stonybrook, U. Colorado/Boulder, and STScI. Substantial complementary internal institutional support is gratefully acknowledged from all of the participating institutions.

Table 3: The Stellar Imager Vision Mission Team

- **Development led by NASA/GSFC in collaboration with:**

Ball Aerospace & Technologies Corp.	Lockheed Martin Advanced Tech. Center
NASA's Jet Propulsion Laboratory	Naval Research Laboratory/NPOI
Northrop-Grumman Space Technology	Seabrook Engineering
Sigma Space Corporation	Smithsonian Astrophysical Observatory
Space Telescope Science Institute	State Univ. of New York/Stonybrook
Stanford University	University of Colorado at Boulder
University of Maryland	University of Texas/Arlington

- **Institutional and topical leads from these institutions include:**

  K. Carpenter (PI), C. Schrijver, R. Allen, A. Brown, D. Chenette, D. Mozurkewich, K. Hartman, M. Karovska, S. Kilston, J. Leitner, A. Liu, R. Lyon, J. Marzouk, R. Moe, N. Murphy, J. Phillips, F. Walter

- **Additional science and technical collaborators include:**

  T. Armstrong, T. Ayres, S. Baliunas, C. Bowers, G. Blackwood, J. Breckinridge, F. Bruhweiler, S. Cranmer, M. Cuntz, W. Danchi, A. Dupree, M. Elvis, N. Evans, C. Grady, F. Hadaegh, G. Harper, L. Hartman, R. Kimble, S. Korzennik, P. Liewer, R. Linfield, M. Lieber, J. Leitch, J. Linsky, M. Marengo, L. Mazzuca, J. Morse, L. Mundy, S. Neff, C. Noecker, R. Reinert, R. Reasenberg, D. Sasselov, S. Saar, J. Schou, P. Scherrer, M. Shao, W. Soon, G. Sonneborn, R. Stencel, B. Woodgate

- **International Collaborators include:**

  J. Christensen-Dalsgaard, F. Favata, K. Strassmeier, O. Von der Luehe

- **Student Participants include:**

  Linda Watson, Darin Ragozzine, Mikhail Dhruv, Fonda Day

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